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Heavy flavour physics —selected issues

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Abstract : Experimental results on heavy flavour physics from various experiments have been considered. Three issues, namely, search for rare B decays, $B^0 - \overline{B}^0$ oscillation, and b and c quark asymmetry measurements in Z decays have been covered [1].

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1. Rare B decays

There are three ways to look for physics at large mass scales. The most obvious is to increase the primary interaction energy and search for direct production of massive states. The other two options, not requiring this increase in primary energy, are precision measurements of some decay widths and search for rare decay modes by accumulating enough statistics at low energies making large mass scales accessible indirectly. Thus rare decays act as pretty powerful microscope to probe short distance phenomenon often kinematically unaccessible to even most powerful accelerators at a given time. For example, the lower mass limit on charged higgs in two Higss doublet model coming from $b \to s\gamma$ decays is the best limit. In this report, we consider a set of rare B decay searches performed at Υ energy, at LEP and Tevatron by various collaboration experiments. To set the working definition, all those b flavoured hadron decays that involve $b \not\to c$ transition are called rare B decays, the branching ratio being at the level of $\leq 10^{-4}$. Of particular interest are effective flavour changing neutral current, FCNC, decays not allowed at tree level and possible only *via* higher order effects in SM. These measurements probe tiny elements of the CKM mixing matrix such as $|V_{ub}|$, $|V_{td}|$ *etc.* The exclusive decays are of

[1] Due to lack of space the last topic is dropped from this write-up. This is covered elsewhere [1]

special interest as they put much tighter control over theoretical predictions [2,3]. In the following a brief summary of results on these searches is provided.

1.1. Charmless hadronic decays :

These decays are supposed to occur *via* external and internal W emissions, the latter being colour suppressed (Figure 1). The decay rates expected in the two cases are at the level of

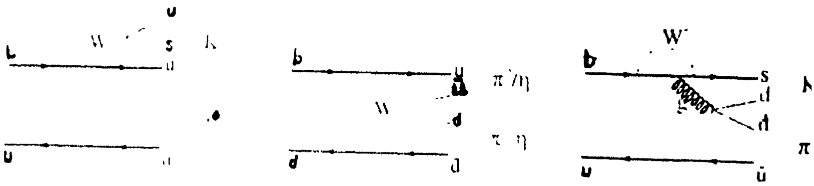

Figure 1. Hadronic B decays within the framework of SM.

10^{-5} and 10^{-7}, respectively [4]. Various experiments have looked for these decays. CLEO [5], DELPHI [6] and ALEPH [7] have definite signals from neutral B decays to two charged hadrons as the efficiency is better in this case. CLEO has observed $B_d^0 \to \pi^+\pi$ and $B_d^0 \to K^+\pi$. They report the integrated branching ratio for $B_d^0 \to h^+h^-$ as $(1.8^{+0.6+0.2}_{-0.5-0.3} \pm 0.2) \times 10^{-5}$. The main problem in this case is continuum background. Signal obtained at LEP is much cleaner due to secondary vertexing, however signal from B_d^0 and B_s^0 can not be distinguished at this stage due to small mass difference between the two. DELPHI [6] report $B_{d,s}^0 \to \pi^+\pi$, $K^+\pi^- = (2.8^{+1.5}_{-1.0} \pm 0.2) \times 10^{-5}$. ALEPH can not distinguish between K and π and report [7] $B_{d,s}^0 \to h^+h^- = (1.7^{+1.0}_{-0.7} \pm 0.2) \times 10^{-5}$. Note that these channels will be relevant for CP violation studies and thus a precise knowledge of these branching ratios is urgent.

1.2. Electromagnetic penguins and extensions :

A variety of possibilities exist like $B \to K^*\gamma$, $B \to \rho\gamma$ and $B \to K^*l^+l^-$, $B \to \rho l^+l^-$ *etc.* with expected Br ratio at the level of ~ 10^{-5}. Few diagrams are shown in Figure 2. CLEO is

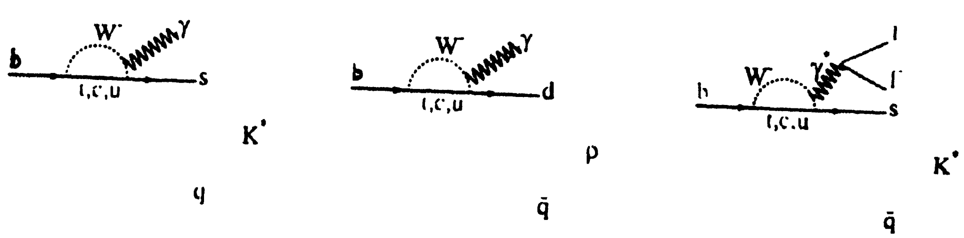

Figure 2. Electromagnetic penguin decay B and extension.

the only experiment to have definite signals in various exclusive channels. The current numbers are :

$$B^0 \to K^{*0}\gamma = (4.4 \pm 1.0 \pm 0.6) \times 10^{-5}$$

$$B^- \to K^{*-}\gamma = (3.8^{+2.0}_{-1.7} \pm 0.5) \times 10^{-5}$$

$$B \to K^*\gamma = (4.2 \pm 0.8 \pm 0.6) \times 10^{-5}$$

Considering the inclusive number for all b flavoured hadron decays, they report $b \to s\gamma =$ $(2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$. Compared to this, the SM estimates summarised in [2,3] lead to $b \to s\gamma = (3.48 \pm 0.31) \times 10^{-4}$. Another number that is of interest for theoretical comparisons is the ratio $R_{K^*} = \Gamma(B \to K^*\gamma)$/over $\Gamma(B \to X_s\gamma)$ as most of the systematics cancel in the ratio. CLEO report $R_{K^*} = 0.181 \pm 0.068$. Theoretical estimates of this number vary between 0.13–0.20.

For other difficult channels like $B \to \rho\gamma$ and $B \to \omega\gamma$ CLEO has placed the first limits. At B factories these modes are expected to be measured pretty accurately, putting stringent constraints over theory.

1.3. Gluonic penguins :

In contrast to the electromagnetic penguins, gluonic penguins are more difficult to identify as gluon can fragment to jet in case of external emission. However in case of colour suppressed internal diagrams, one may still observe some exclusive states like $B \to X_s\phi$ (Figure 3). A study of this mode is interesting as any enhancement of this mode may be an

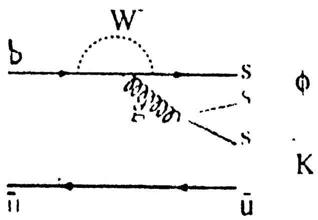

Figure 3. Gluonic penguin decay of B. Only the special case of internal gluon emission is shown.

indication why semileptonic branching ratios of B are lower than expected. CLEO [8] has reported the first limit : $B \to X_s\phi < 2.2 \times 10^{-4}$ at 90% CL.

1.4. Pure leptonic decays :

These are interesting decays (Figure 4) and theoretically cleanest to calculate and hence extract CKM elements. Theoretical estimates summarised in [2] lead to

$$B_s^0 \to \tau^+\tau^- \sim 7 \times 10^{-7}$$

$$B_s^0 \to \mu^+\mu^- \sim 4 \times 10^{-9}$$

$$B_s^0 \to e^+e^- \sim 8 \times 10^{-14}$$

The B_d^0 decay rates are about 4–5 times lower. First mode is more difficult as one needs to identify both τ's. The last one being extremely small, leaves only the μ channel most interesting. Attempts have been made at LEP and Tevatron, the latter producing the largest number of B's. The hostile environment at Tevatron does not create serious problem of detection in μ, μ channel. The best limits at 90% CL come from CDF experiment [9].

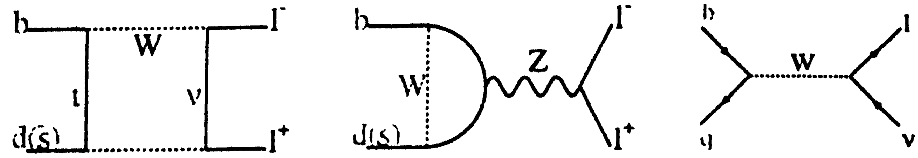

Figure 4. Pure leptonic B decays. First two diagrams involve neutral B decays to a pair of charged leptons whereas the last one involves charged B decay to a charged lepton and corresponding neutrino.

$$B_d^0 \to \mu^+\mu^- < 2.6\times10^{-7}$$

$$B_s^0 \to \mu^+\mu^- < 7.7\times10^{-7}$$

We expect that Run II at Tevatron will improve these limits by one order of magnitude and if lucky CDF/D0 experiments may even detect this mode. Note that B factories have no chance to see this mode. Definite measurements are expected at LHC where even at low luminosity run one will have about 10^{12} $B\overline{B}$ produced in one year.

The last diagram, $B \to \tau\nu_\tau$ has the largest branching ratio. The $L3$ experiment [10] at LEP has the best limit :

$$B^- \to \tau\nu_\tau < 5.7\times10^{-4} \text{ at } 90\% \text{ CL.}$$

Whenever measured, this will provide the direct experimental determination of B decay constant, f_B, knowing CKM element $|V_{ub}|$ and B lifetime, τ_B, from other measurements.

1.5. *Radiative decays :*

These are special decay modes involving short and long distance effects (Figure 5) and have similar potential of measuring $|V_{td}|$ and $|V_{ts}|$ as pure leptonic modes above. Only

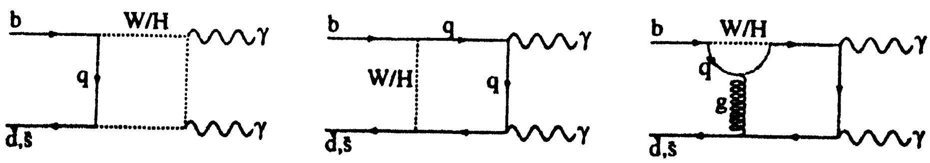

Figure 5. Pure electromangetic B decays. Some interesting examples are shown. Many more are possible.

$L3$ experiment at LEP has looked into this mode exploiting its powerful ECAL. They report [11] :

$$B_d^0 \to \gamma\gamma < 3.95\times10^{-5} \text{ at } 90\% \text{ CL.}$$

$$B_s^0 \to \gamma\gamma < 14.8\times10^{-5} \text{ at } 90\% \text{ CL.}$$

A definite measurement is expected at LHC by CMS experiment that has best electromagnetic calorimeter and good π^0 rejection capability.

We conclude that experimental progress in the study of rare B decays has been impressive over the last few years. In particular :

$B \to X_s \gamma$ is well measured.

$B^0 \to h^+h^-$ is established.

$B^0 \to \mu^+\mu^-$ and $B^0 \to \gamma\gamma$ have been searched and decent limits have been placed. Many more exciting results are expected in near future from B factories and Tevatron Run II.

2. $B^0 - \overline{B}^0$ oscillation/mixing

Neutral meson-antimeson oscillations are clean signals to realise second order weak transitions that amount FCNC processes. Like K^0, the B^0 weak eigenstates are a linear combination of mass eigen states. Thus,

$$|B^0\rangle = \frac{|B1\rangle + |B2\rangle}{\sqrt{2}} \text{ and } |\overline{B}^0\rangle = \frac{|B1\rangle - |B2\rangle}{\sqrt{2}}$$

where the two states have mass difference $\Delta m = M1 - M2$ and similarly a lifetime difference which is considered to be small and neglected in this case. Thus a beam of pure B^0 studied as a function of time evolves into two components, a fraction of which is inferred from the final state decay products. This probability can be expressed as follows :

$$P\left(B^0 \to \overline{B}^0\right)_t = \frac{1}{2}e^{-t\Gamma/\hbar}\left(1 - \cos \Delta mt/\hbar\right)$$

$$P\left(B^0 \to B^0\right)_t = \frac{1}{2}e^{-t\Gamma/\hbar}\left(1 + \cos \Delta mt/\hbar\right)$$

where $\Gamma = \left(\frac{\hbar}{\tau}\right)$ is the decay width. For the detector resolution where only time integrated measurements are possible :

$$P\left(B^0 \to \overline{B}^0\right) = \chi = \frac{1}{2}\frac{\frac{\Delta m}{\Gamma}}{1 + \left(\frac{\Delta m}{\Gamma}\right)}$$

where χ is called the mean mixing parameter and $\frac{\Delta m}{\Gamma} = x$, the oscillation frequency. For reasonably large oscillation frequency ($x > 5$), the time integrated measurement loses its sensitivity as $\chi \simeq 1/2$, the mixing is maximal.

It is found that $\frac{\sigma_S}{S} \approx 24\%$ for small $(P_{(D^*,l)}, m_{(D^*,l)})$ and $\frac{\sigma_S}{S} \approx 5\%$ for large $(P_{(D^*,l)}, m_{(D^*,l)})$. The charge correlation of production time and decay times tags is studied as a function of time (see Figure 7). For an ideal situation

$$R(t) = \frac{N_{mix}(t)}{N_{tot}(t)} \alpha \ 1 - \cos(\Delta mt)$$

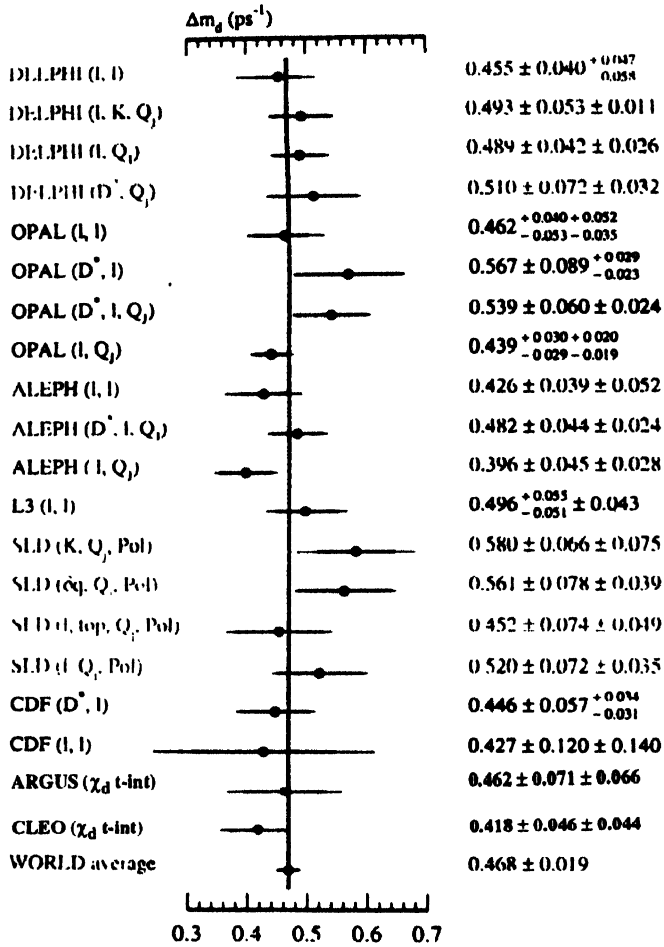

Figure 8. A summary Δm_d measurements by various experiments exploiting different type of techniques.

However due to resolution effects and backgrounds the oscillation amplitude is damped. OPAL has parametrised the resulting damped amplitude as follows.

$$R(t) = f + \frac{1 - 2f}{1 + N_x(t)/N_0(t)} \frac{1 - \cos(\Delta mt)}{2}$$

where f is the mistag probability and $N_0(t)$ and $N_x(t)$ are the number of neutral and charged B's decaying at time t with their corresponding lifetimes τ's. From a fit to the data, they determine $\Delta m_d = 0.539 \pm 0.060 \pm 0.024\, ps^{-1}$, and $f = 0.277 \pm 0.023$. The value of f is consistent with that expected from MC (= 0.28). The largest systematics comes from the knowledge of charged B *vs* neutral B fraction in the sample.

A summary of the Δm_d (ps^{-1}) measurements from various experiments, exploiting several tagging procedures, is given in Figure 8. The time integrated measurements at $\Upsilon(4S)$ [20,21] are also given in the same figure, using B^0 life time. The world average is :

$$\Delta m_d = 0.468 \pm 0.019\, ps^{-1}$$

This is a very precise measurement and translated to mass units corresponds to :

$$\Delta m_d = 3.08 \pm 0.12 \times 10^{-4}\,\mathrm{eV/c^2}$$

This measurement can be used to extract the CKM element V_{td}, exploiting equation (1), now that the top mass is known. However, as it turns out, unless decay matrix element factors like $\mathcal{B} f_B^2$ and η_{QCD} are better understood, full potentials of this precise measurement can not be realised. These experimental results demand serious theoretical efforts in understanding B decays.

As for as B_s oscillations are concerned, efforts are being made by LEP experiments. One way is to isolate this second fast component in oscillation amplitude. Another way is to use identified B_s candidates. Both methods have been used. Considering the example from ALEPH [22], they have a total 277 $B_s \to D_s^- l^+ \nu$ candidates where the expected background is 79 ± 5 events. For the purpose of production time flag, lepton and jet charge combinations are used from opposite hemisphere. Added information is used taking fast strange light meson in the same hemisphere. Their analyses leads to exclusion of $\Delta m_s < 6.6\, ps^{-1}$ at 95% CL. Combined with other LEP results, in particular DELPHI [23], $\Delta m_s < 9.2\, ps^{-1}$ is excluded at 95% CL. A finite measurement is unlikely before LHC.

3. Conclusions

Impressive progress has been made in heavy flavour physics studies, in particular in the area of B physics. Rare B decay searches that test FCNC processes have received special attention. Measurements of branching ratios like $b \to s\gamma$ (inclusive) and $B \to K^*\gamma$ (exclusive) have been considerably improved. Exclusive decays like $B^0 \to h^+h^-$ have been established. A knowledge of these mode is important for CP violation studies. Decent limits on $B^0 \to \mu^+\mu^-$ and $B^0 \to \gamma\gamma$ have been placed, the latter for the first time. Attempts have been made to look for gluonic penguins.

$B^0 - \overline{B}^0$ oscillation has been studied in great detail. Time dependence of B_d oscillation is well established and the measurement of mass difference/oscillation frequency is so precise that it demands better theoretical progress in understanding B decays if these measurements are to be potentially exploited.

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